Reply to Comments on "Seasonal Variation of the Physical Properties of Marine Boundary Layer Clouds off the California Coast"

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Based on the strong similarity in microphysical differences between summer–winter marine boundary layer (MBL) clouds and the closed–open mesoscale cellular convection (MCC), Liu (2010)'s comments suggest that there is plausibly a microphysical mechanism, in addition to the macrophysical mechanism discussed in Lin et al. (2009), that is responsible for the seasonal contrast of the boundary layer structure and MBL cloud properties.

Given the Moderate Resolution Imaging Spectroradiometer–Clouds and the Earth's Radiant Energy System (MODIS–CERES) retrieval of mean liquid cloud effective radius r_e, together with the cloud liquid water path (LWP) and cloud thickness H as presented in Lin et al. (2009), the cloud droplet number density N and drizzle rate P can be estimated using (1), (2), and (6) in Liu (2010)'s comments. Without losing generality, we assume the more commonly used $b_e = 1/3$ and use $a_e = 66.83$ from Martin et al. (1994) for maritime stratocumulus clouds. See Liu's comments and the cited references for more discussion about the relations and the coefficients.

The effective radius and the calculated number density as well as the drizzle rate are shown in Fig. 1. Indeed, as predicted in Liu's comments, the MBL clouds off the California coast in summer are not only with higher liquid water content L but also with smaller r_e, larger N, and smaller P than those in winter. Figure 1 additionally shows that the spatial downstream variations of these microphysical properties along the cross section for each season are similar to the seasonal contrast of these variables. The summer-to-winter variation mirrors the transition from closed to open MCCs, as discussed in Liu (2010). Considering that the microphysical sensitivity of the cloud-base precipitation rate becomes weaker for clouds with stronger precipitation (Kubar et al. 2009; Wood et al. 2009), an alternative formulation with weaker dependence on microphysical properties (Van Zanten et al. 2005) is also used to estimate the drizzle rates. The seasonal difference is very similar (not shown). The higher drizzle rate during the winter in this region is also supported by multiyear MODIS retrievals, with drizzle frequency being higher among MBL cloud scenes during off-peak season for stratocumulus clouds (Jensen et al. 2008). The coincidence of higher drizzle rate and higher inversion height during winter appears to be consistent with the positive correlation between cloud-top height and drizzle frequency, as reported in Leon et al. (2008). Note that the equations for the estimation of N and P are for cloud-scale processes and highly nonlinear. The numbers that are derived based on the long-term averaged L and r_e should be interpreted with caution.

However, there are also important cloud properties that cannot be explained in this analogy. First, for MCCs, along the cross section in the summer, the increasing drizzle rate should be associated with decreasing cloud fraction, because in comparison with closed MCCs, open MCCs usually have about 30% less cloud fraction (Wood and Hartmann 2006). But this is not the case in the seasonal variation: higher rate of drizzle in the summer is associated with larger cloud fraction along the cross section (Fig. 5a in Lin et al. 2009). Furthermore, in the winter,

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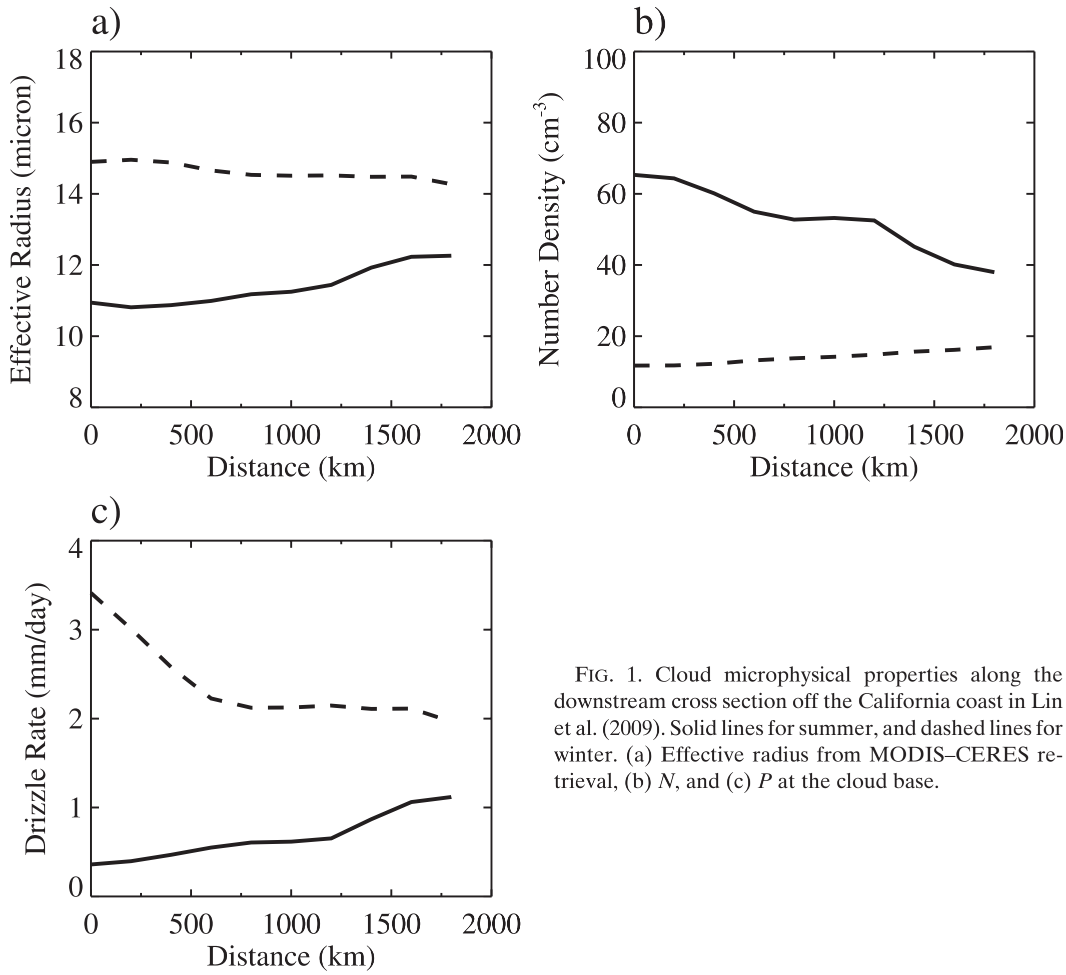

FIG. 1. Cloud microphysical properties along the downstream cross section off the California coast in Lin et al. (2009). Solid lines for summer, and dashed lines for winter. (a) Effective radius from MODIS–CERES retrieval, (b) N, and (c) P at the cloud base.

the drizzle rate is the largest near the coast (Fig. 1b), but open MCCs are more frequently observed some distance away from the coast (Wood and Hartmann 2006).

Second, the seasonal contrast of the primary boundary layer property—the inversion height—cannot be explained by the closed–open cellular analogy. When pockets of open cells (POCs) form within extensive overcast stratocumulus, the ensuing drizzling would thin or break the cloud layer, reducing the cloud-top radiative cooling; this would in turn weaken the turbulence and entrainment, promoting the decoupling of the boundary layer. As a result, the inversion height should be lower in the open POCs (e.g., Bretherton et al. 2004). Instead, Lin et al. (2009) shows the inversion height is significantly higher during the winter.

Open MCCs are generally considered to be either advected from midlatitude systems or formed as POCs within overcast stratocumulus (Wood et al. 2008). For the former, the microphysical mechanism is not directly responsible for the presence of open MCC in the study region, particularly when the local microphysical effect is concerned in this discussion. For the latter, in the winter season, the boundary layer, being close to a permanently decoupled state (see Lin et al. 2009) with much higher inversion height than in the summer, is not conducive to the formation of overcast stratocumulus. This is also found by Jensen et al. (2008) that overcast conditions are much less frequent during winter for the study region. The lack of overcast conditions itself would limit the frequency occurrence of POCs, even without invoking the microphysical mechanism as a dominant factor in governing the seasonal variation of boundary layer structure and cloud properties. This, however, should not exclude the plausible roles by the microphysical processes in modulating the boundary layer and microphysical/macrophysical cloud properties at seasonal scale. The fact that aerosol loading is slightly higher in this region in the summer than in the winter (e.g., Yu et al. 2003; Jaffe et al. 2005; Zhang et al. 2005; Remer and Kaufman 2006) is also consistent with the contrast of microphysical properties, as shown in Fig. 1, which further serves as an indication of potential aerosol indirect effect in regulating the cloud variations at seasonal scale. The distinct seasonal contrast of these cloud properties therefore provides a rich laboratory to investigate the different underlying physical processes, which is a necessary step to understand the cloud–climate feedback problem.

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